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GREEN CHEMISTRY: A PRIMER

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ABSTRACT: *With mounting concerns over the state of our planet, there is continuing demand that chemists and chemical engineers should develop greener chemical processes and products. In the 1990s, with the growing awareness of the hazardous impacts of the chemical industry, the green chemistry revolution was launched by American chemists Paul T. Anastas and John Warner. Green chemistry is the kind of chemistry that seeks to minimize pollution, conserve energy, and promote environmentally friendly production. This paper provides a brief introduction to green chemistry.*

KEY WORDS: *green chemistry, sustainable chemistry, green engineering*

I. INTRODUCTION

The chemical industry touches every aspect of our modern life. Our quality of life depends on chemical products and processes. Unfortunately, the chemical industry's traditional approach to producing goods has been regarded unsafe and unsustainable. Green chemistry efficiently utilizes materials, eliminates waste, and minimizes the use of hazardous processes and substances. It plays a transformative role in the chemical industry. The concept of green chemistry is a relatively new idea. Green chemistry involves the development of chemical products and processes that reduce or eliminate the use of hazardous substances. Green chemistry is also known as sustainable chemistry, clean chemistry, and benign by design chemistry [1]. It focuses on the environmental impact of chemical products and processes. It reduces toxicity, minimizes waste, and saves energy.

Green chemistry is not confined to the industrial sector. It applies to all areas of chemistry including organic chemistry, inorganic chemistry, biochemistry, analytical chemistry, and physical chemistry. It is an interdisciplinary area drawing on knowledge from chemists, chemical engineers, toxicologists, and ecologists. It has evolved from being an academic research effort to become a practice supported by academia, industry, and government. In the United States, regulatory programs play a major role in shaping the development of green chemistry. The Environmental Protection Agency (EPA) was formed in 1970 and charged with protecting human and environmental health through setting and enforcing environmental regulations. The EPA has played a significant role in fostering green chemistry through its pollution prevention programs and funding. The EPA also demands that chemists and engineers should design chemical processes and products in a way that prevents pollution and avoids the creation of toxic by-products and waste. Since 1996, the United States has given an annual award, the Presidential Green Chemistry Challenge Award, to promote and reward significant achievements in green chemistry.

II. PRINCIPLES OF GREEN CHEMISTRY

In 1998, Paul Anastas and John C. Warner published twelve principles to guide the practice of green chemistry. The principles address a wide range of approaches to reduce the environmental and health impacts of chemical production. They provide an early template for what would make a greener chemical or product. The twelve principles are illustrated in Figure 1 and explained as follows [2-4]:

1. Prevention: Preventing waste is better than treating or cleaning up waste after it is created.
2. Atom economy: Synthetic methods should try to maximize the incorporation of all materials (atoms) used in the process into the final product.
3. Less hazardous chemical syntheses: Synthetic methods should avoid using or generating substances toxic to humans and/or the environment.
4. Designing safer chemicals: Chemical products should be designed to achieve their desired function while being as non-toxic as possible.
5. Safer solvents and auxiliaries: Auxiliary substances should be avoided wherever possible and as non-hazardous as possible when they must be used.
6. Design for energy efficiency: Energy requirements should be minimized, and processes should be conducted at ambient temperature and pressure whenever possible.

7. Use of renewable feedstocks: Whenever it is practical to do so, renewable feedstocks or raw materials are preferable to non-renewable ones.
8. Reduce derivatives: Unnecessary generation of derivatives, such as the use of protecting groups, should be minimized or avoided if possible; such steps require additional reagents, lessen atom economy, and may generate additional waste.
9. Catalysis: Catalytic reagents that can be used in small quantities to repeat a reaction are superior to stoichiometric reagents (ones that are consumed in a reaction).
10. Design for degradation: Chemical products should be designed so that they do not pollute the environment; when their function is complete, they should break down into non-harmful products.
11. Real-time analysis for pollution prevention: Analytical methodologies need to be further developed to permit real-time, in-process monitoring and control before hazardous substances form.
12. Inherently safer chemistry for accident prevention: Whenever possible, the substances in a process, and the forms of those substances, should be chosen to minimize risks such as explosions, fires, and accidental releases.

These principles are being put into practice in all walks of science since they provide a recipe for efficient manufacturing and a safe environment.

III. APPLICATIONS

Green chemistry is impacting the chemical industry and other sectors such as agriculture, healthcare, automotive, electronics, energy, and materials.

- **Pharmaceutical industry:** Green chemistry is a strong ally with the pharmaceutical industry. The main goal of green chemistry is to reduce or eliminate waste in the manufacture of drugs. The pharmaceutical industry was among the first to recognize the value of green chemistry. For example, a pharmaceutical company can produce more ibuprofen in less time and with less energy, resulting in increased profits. Green chemistry can also be used to develop innovative drug delivery methods [5]. The pharmaceutical industry is seeking ways to develop medicines with less harmful side-effects.
- **Agriculture:** Sustainable agriculture meets the demands for agricultural output at socially acceptable economic and environmental costs. The use of fertilizers can be reduced by timing it to the needs of the crop, lowering the environmental impact of large-scale agricultural operations.
- **Energy:** Green chemistry also plays an important role in alternate energy via the production of solar cells, fuel cells, and batteries for energy storage. Transportation alone accounts for one fourth of energy consumption and two thirds of oil usage in the US. The photovoltaic industry is leading the clean-energy sector.
- **Leisure industry:** Chemistry provides inexpensive materials for golf, fishing, etc. Tourism activities can have negative impacts when the environment is unable to cope with the increased population due to tourist visitors. Tourism can contribute to the depletion of natural resources such as water, food, and energy and increase the local generation of waste. Green chemistry can contribute to the sustainability of the leisure industry [6].

Green chemistry is also regarded as a powerful tool for evaluating the environmental impact of nanotechnology.

IV. METRICS

To measure the environmental impact of chemical processes and track green chemistry progress, some tools are needed. Green chemistry can be defined using metrics which can be used to quantify greener processes and products. In other words, the metrics are used to determine how green is green [7]. Such an effort would require the collaboration of chemists, policy makers, educators, and businesses [8]. These metrics include ones for mass, energy, hazardous substance reduction, and life cycle environmental impacts.

V. BENEFITS AND CHALLENGES

Green chemistry is a tool for achieving sustainability. It is sustainable in the sense that it serves the needs of today's generation without endangering the ability of future generation to meet their own needs. Green chemistry is beneficial to our planet. Adopting green chemistry gives us an opportunity to create a safer laboratory and living environment. It provides greater efficiency in the chemical industry. It has the potential to improve the quality of different technologies used in chemical industry.

Going green can benefit us in the following ways [9]. Using sustainable and renewable resources for reactants and catalysts preserves resources for future generations. When less waste is produced in a reaction, there is less potentially hazardous material being released into the environment. Avoiding the creation of hazardous environmental situations will lessen the likelihood of class actions lawsuits, which are expensive and damaging to a company's reputation. The green chemistry revolution presents several challenges to chemists and chemical engineers. The major challenges confronted by green chemistry innovations include [10]: economic and financial, (2) regulatory, (3) technical, (4) organizational, (5) cultural, and (6) definition and metrics. A large part of the chemical industry is capital-intensive. Large companies are slow and reluctant to switch to new technologies due to the upfront costs involved. It is also a challenge for industries to synthesize non-harmful products since the harmful traits are often linked to the desired functionality of the products.

Some potential downsides of green chemistry include the following [9]. When new, greener reactions are developed, new equipment or even entirely new chemical plants may be necessary. The set-up costs can be prohibitive. Unintended consequences can also have severe impacts on the public. Older chemical processes have been around long enough that their potential hazards are well understood. Newer materials may appear greener at first, but problems may reveal themselves later.

VI. CONCLUSION

Green chemistry, also known as environmentally benign chemistry, focuses on the design of chemical processes and products to minimize their inherent hazard. It has emerged as an important aspect of all chemistry and it is the future of chemistry. The main goal of green chemistry is to reduce or eliminate waste in the manufacture of chemicals and its allied products. The chemical industry has risen to the occasion by replacing traditional processes with greener alternatives. The successful implementation of green chemistry requires the cooperation of the academia, industry, government, and society. Chemical societies worldwide have recognized the importance of green chemistry. They promote it through journals, conferences, educational activities, and the formation of the Green Chemistry Institute chapters. Several institutions now offer courses and degrees on green chemistry. Today's students will significantly benefit from the introduction of green chemistry in the curriculum [11, 12]. More information about green chemistry can be found in Green Chemistry and Current Opinion in Green and Sustainable Chemistry, two journals exclusively devoted to it. One should also consult books in [3, 13-17] and several other books in Amazon.com.

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Figure 1. The principles of green chemistry [4].